Improving Surface Flux Parameterizations in the Navy's Coastal Ocean Atmosphere Prediction System

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LONG-TERM GOAL

The long-term goal is to understand the physical processes that critically regulate the coupling between the oceanic and atmospheric boundary layers and develop advanced parameterizations of this interaction for a new generation of coupled ocean-atmosphere models.

OBJECTIVES

The objective of this research is to improve the surface flux and boundary layer turbulence parameterization in the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®[1]) for low- and high-wind events over the ocean in the context of air-sea interaction. Special emphasis will be placed on flux parameterizations in low-wind regimes in collaboration with the Coupled Boundary Layer Layers/Air-Sea Transfer (CBLAST) Defense Research Initiative community.

APPROACH

There are two complementary and strongly interacted components in our study: modeling and observational efforts. Our first approach is to use COAMPS as a tool in understanding the physical processes and developing new parameterizations for the surface and boundary layer turbulence mixing. e provide real-time COAMPS weather forecasts for each intensive observational period of the CBLAST-Low field experiments, and therefore establish a focused model dataset, which can be used, with the measurements, to evaluate the model physics and investigate the impacts of the interaction on the mesoscale weather prediction. e also use various single column versions of COAMPS and experiment data to study the detailed turbulence processes, and to develop new parameterizations. The second approach involves the use of the observational study that included measurements in the boundary layer and upper air at the CBLAST Nantucket site. These measurements are critical in the evaluation of the COAMPS forecast and development of the new parameterizations. They also provide a valuable data source for the process study of the air-sea interaction in that area.

[1] COAMPS® is a registered trademark of the Naval Research Laboratory.

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14. ABSTRACT
The long-term goal is to understand the physical processes that critically regulate the coupling between the oceanic and atmospheric boundary layers and develop advanced parameterizations of this interaction for a new generation of coupled ocean-atmosphere models.

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WORK COMPLETED

1. Impact of sea surface temperature (SST) variability on atmospheric boundary layer flow

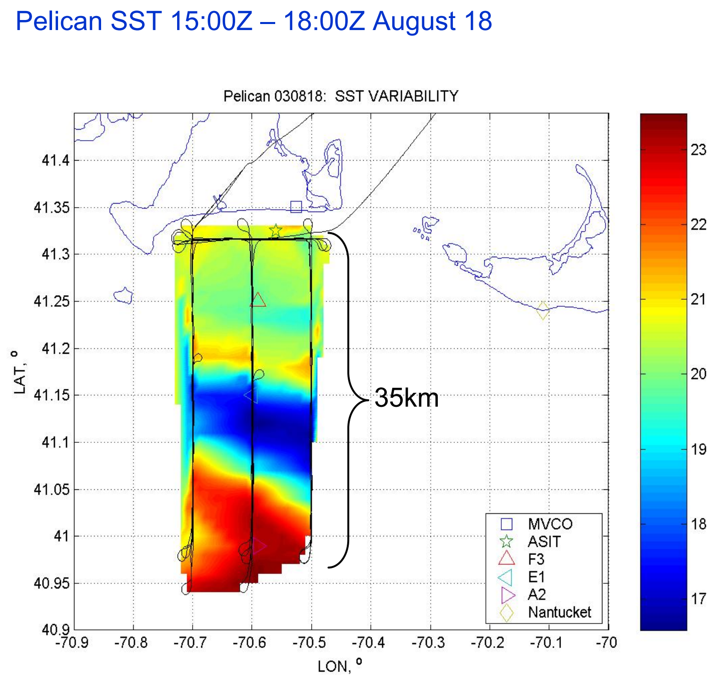


Figure 1. Aircraft observations showed strong SST variability in the area 15 km to the south of Martha's Vineyard Island on August 18 2003. The wind was coming from the northeast.

Some aircraft observations in the CBLAST-Low field experiment in August 2003 demonstrated significant small-scale SST variability (6^{o}C over 10km) and corresponding variabilties of air temperature and winds, as shown in Fig. 1. It is generally understood that SST variability has important implications on the marine boundary layer structure (e.g., Hayes et al, 1989; and Mahrt *et al*, 2004). These measurements provide excellent cases for a more comprehensive understanding on the impact of the SST variability on the atmospheric boundary layer. We included these SST measurements and additional satellite data in the COAMPS ocean data assimilation system, and then simulated the evolution of the marine boundary layer structure on 18 August 2003 using a high-resolution application of COAMPS (1, 3, 9, and 27 km nested grids). To understand the impact of the SST variability, we also simulated the same CBLAST period but without including the SST variability data. Both simulations were compared with the aircraft observations.

2. *A comparative study of fog events in the CBLAST experiment and the U.S. west coast.*

The formation of fog over the ocean has been investigated by numerous studies. The focus has been on its formation and dissipation for an individual event. In this study, we compared and contrasted two fog events; the first occurring in conjunction with a coastally trapped disturbances (CTD) along the west coast of the U. S. on 15 June 2000, and the second occurring over the area south and east of Cape Cod, MA on 21 August 2003 during the CBLAST experiment. In both cases, we used the COAMPS mesoscale model to simulate the events. The results from the two simulations were compared and analyzed. We particularly investigated the contribution of latent heat generation to the buoyancy flux, which is the basic driving force of the low-level clouds.

3. Synthesis and analyses of the Nantucket measurements

CBLAST measurements, particularly those from the Nantucket site, were further analyzed to understand the variation of turbulent fluxes in response to forcing from mesoscale variations and local land surface near the measurement site. We applied quadrant analysis technique to the sections of the marine air and land-surface internal boundary layer and found distinctive characteristics of the turbulent ejection/sweep eddies and the interaction eddies. Detailed analyses were also made to measurements from August 14, 2003, where rapid evolution of boundary layer vertical structure were observed in response to the surface wind changing from southerly to easterly. This analysis uses measurements from all CBLAST-low sites (Nantucket, Martha Vineyard, Air-sea flux tower, and the nearly-by buoys) and is supported by a COAMPS simulation in the region to define the temporal/spatial variation of the area.

4. *NCOM simulation of CBLAST area*

The CBLAST field experiment provides comprehensive datasets of both atmospheric and oceanic boundary layers for new understanding of the physical processes and model evaluations. The Navy Coastal ocean Model (NCOM) was applied to the CBLAST area with COAMPS atmospheric forcing. We performed one-month long experiments with and without the COAMPS ocean data assimilation. The ocean domain is identical to the inner grid of COAMPS CBLAST real time forecast with 3 km resolution. The NCOM results were evaluated with CBLAST buoy and aircraft data. We found that the cold SST located west of Georges Bank over Nantucket Shoals was simulated in the case with data assimilation. Since tidal forcing was not included in the model, the Nantucket Shoals high tidal energies, which is the main forcing for generating the cold SST by the tidal mixing, are absent. This cold SST feature was then not resolved in the NCOM free run. The cold water was advected from Nantucket Shoals to Martha's Vineyard coast during the passage of low-pressure system, although it didn't move further west in the NCOM simulations for Aug. 18 as it was observed to do.

5. *Implementation of new surface drag coefficients and dissipative heating in hurricane conditions*

During the CBLAST-hurricane meeting in April, 2004, a consensus was reached that the surface drag coefficient increases with 10m wind speed up to 35 ms^{-1} above which the drag is levels-off at 2.5×10^{-3}. It is also generally agreed that the dissipative heating may play a noticeable role in hurricane intensification. For these reasons, we implemented both the drag-level-off and dissipative heating parameterizations. We used the Donelan experiment result (Donelan *et al*. 2004) in our drag coefficient formulation. For the dissipative heating implementation, we derived a consistent set of equations of turbulent kinetic energy and thermodynamic budgets. That is, the dissipative heating term in the energy budget is exactly the same as that in the TKE equation. Therefore, the total energy is conserved in the model atmosphere. This feature is unique among various models that include dissipative heating parameterization. We simulated a number of hurricane cases with the nested grids (5, 15, 45 km). The results are encouraging.

RESULTS

1. *Impact of sea surface temperature (SST) variability on atmospheric boundary layer flow*

Fig. 2 compares the results from COAMPS simulations with and without the aircraft measurements in the ocean data assimilation. Without the aircraft measurements of SST, COAMPS ocean data assimilation system did not produce the SST variability in the area (Fig 2a and 2b). The surface layer is unstable as the control SST is higher than the observed in the area centered around 41.1^{o}N as shown in Fig. 2b. Consequently, the simulation without the SST variability significantly overestimates air temperature and wind speed prediction. Particularly, the wind speed is 20-30 percent more than the observations. Inclusion of the SST observations significantly improves the surface layer structure, i.e., it change the layer from unstable to stable. The stable surface layer significantly suppresses the vertical mixing, leading to a considerable decrease in the downward momentum transport. Consequently, both the predicted wind speed and temperatures in the simulation with the SST variability are significantly improved (Fig. 2c and 2d). The simulated corresponding turbulence variables such as the fluxes and TKE are also compared more favorably with the observations (not shown here). These results clearly show the importance of detailed SST observations in realistic simulations of marine boundary layers under low-to-moderate wind speed regimes.

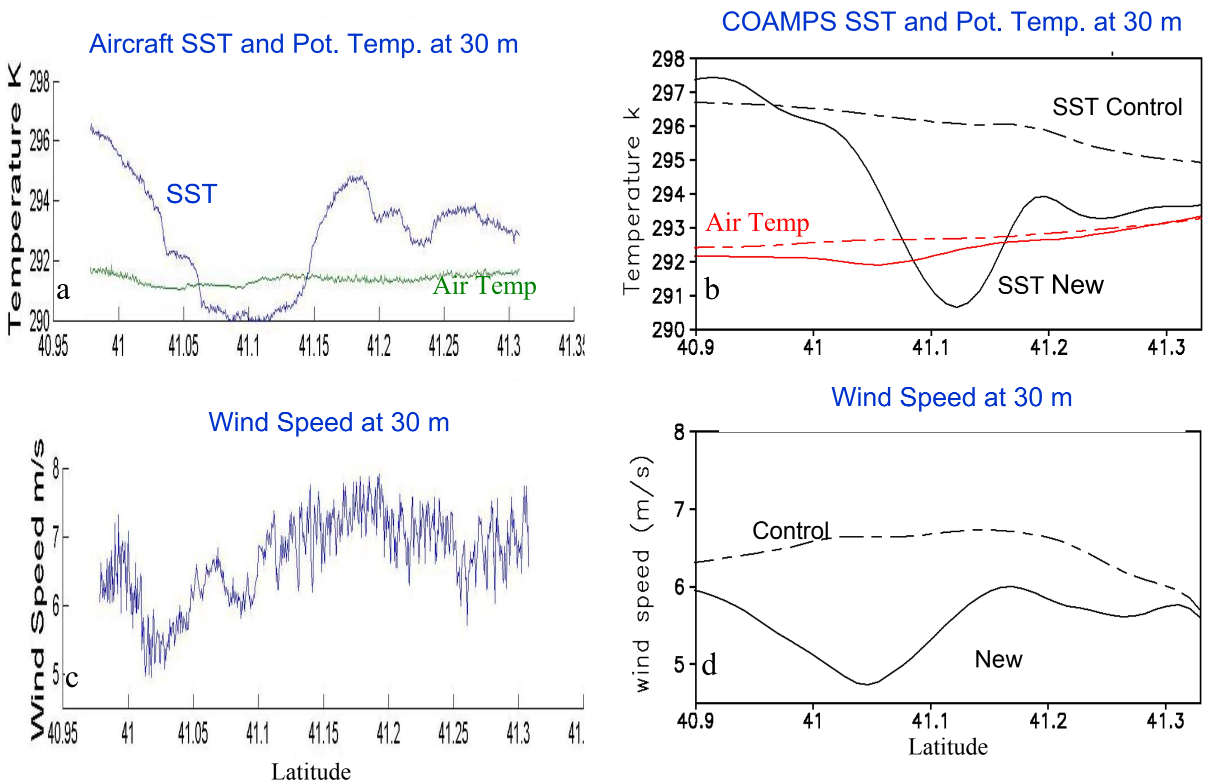


Figure 2. Comparison between COAMPS simulations with and without the aircraft measurement in the ocean data assimilation system. Left: aircraft observations; Right : COAMPS simulations. Control represents the simulation without the aircraft observation data; New represents the simulation with the data. There is a clear contrast between these two simulations. Noticeable is the significant wind speed change due to the cold SST anomaly both in the observations and COAMPS simulations.

2. *Fog study*

Our analysis of the two fog events in CBLAST and CTD showed that the latent heat contributes significantly to the positive buoyancy flux in both cases. In the CBLAST case, in contrast to the CTD case, the distribution of the latent heat contribution shows a banded structure, with alternating bands of positive and negative (or near zero) value. These bands are coincident with changes in the topography of the cloud top, demonstrating a strong connection between the latent heat and the cloud-top entrainment. In addition, the formation of the cloudy mixed layer in CBLAST is due to the overwhelming longwave radiative cooling in the fog layer such that turbulent mixing is significantly enhanced. Consequently, the fog layer lifts away from the surface due to the entrainment mixing at the cloud top.

3. *Analyses of Nantucket observations*

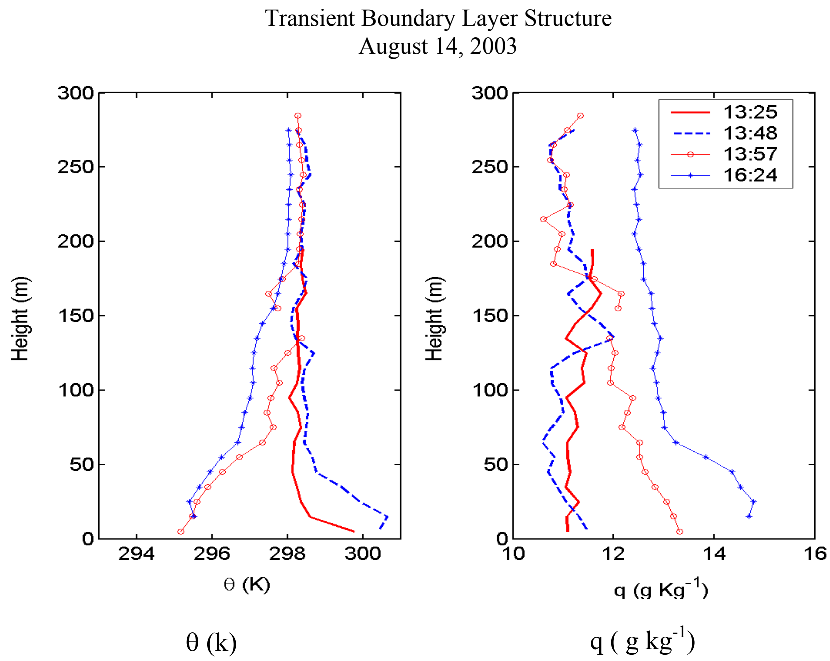


Figure 3. Transient boundary layer behavior. Left: Potential temperature; Right: Water vapor mixing ratio. Different colors represent different time.

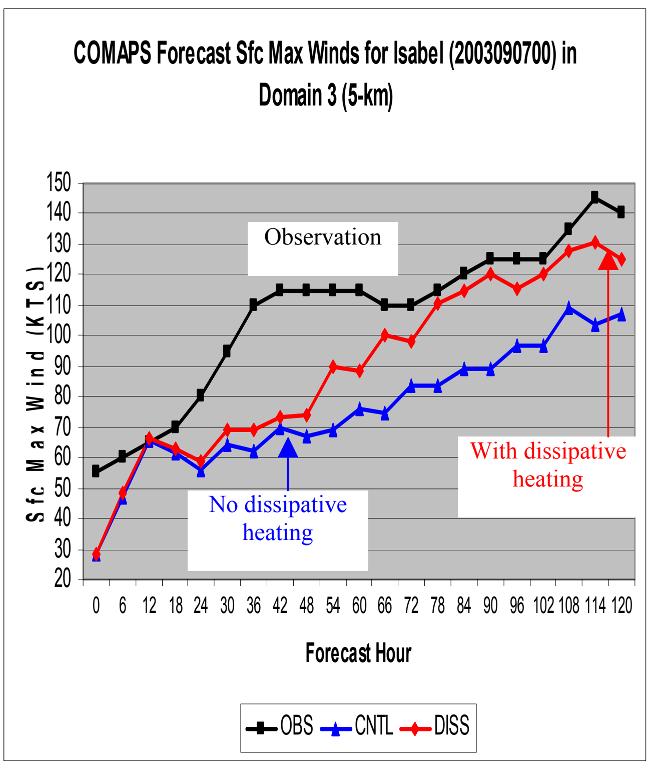
In addition to data analyses in support of COAMPS model evaluation and development of new boundary layer parameterizations, our data analyses effort also focused on understanding the evolving boundary layer structure in response to mesoscale forcing in the measurement area. Fig. 3 shows results from a case analysis where rapid changes in the boundary layer occurred. The lower 100 m of the boundary layer evolved from an unstable boundary layer to a stable boundary layer within a 9-minute time period. This kind of transient behavior is an important feature of the coastal marine boundary layer where the complex topography and land-sea contrast produces the interaction between different air masses. We further decomposed the turbulent perturbation of horizontal and vertical winds into 4 quadrants according to their signs. Our analysis showed that the dominant contribution of the ejection/sweep eddies occurred during midday in southerly wind conditions (land boundary layer).

Corresponding to the rapid cooling of the lower boundary layer cooling (shown in Fig. 3), we found a sharp decrease of the ejection/sweep eddies fluxes and the turbulent heat flux thus reduced to near zero values. This quadrant analysis provides a different perspective on the physical processes that produce the momentum flux.

4. *The implementation of dissipative heating and new drag coefficient improves the COAMPS hurricane simulations*

The 5-day time evolutions of simulated surface maximum winds in the 5-km moving nest are shown in Fig. 4 (left). Over the first two days, the model did not capture the observed intensity, presumably due to the time needed for model spinning-up. The storm of the control run remains significantly weaker than the observed throughout the whole simulation period, i.e., with the maximum surface winds of 90 kts at hour 84, compared to the observed value of 120 kts. For the simulation with the dissipative heating, the storm is intensified at a much more rapid rate than the control run with the maximum surface winds of 116 kts at hour 84, about 26 kts stronger than from the control run. There is also a high correlation between strong surface winds and high values of the dissipative heating rate. The values of dissipative heating reach 100 K/hr in the eyewall region when the surface winds exceed 100 kts after 84 hours into the simulation.

Time series of maximum wind speed of COAMPS Isabel simulation



Distribution of wind speed and dissipative heating rate at the surface of COAMPS Isabel simulation

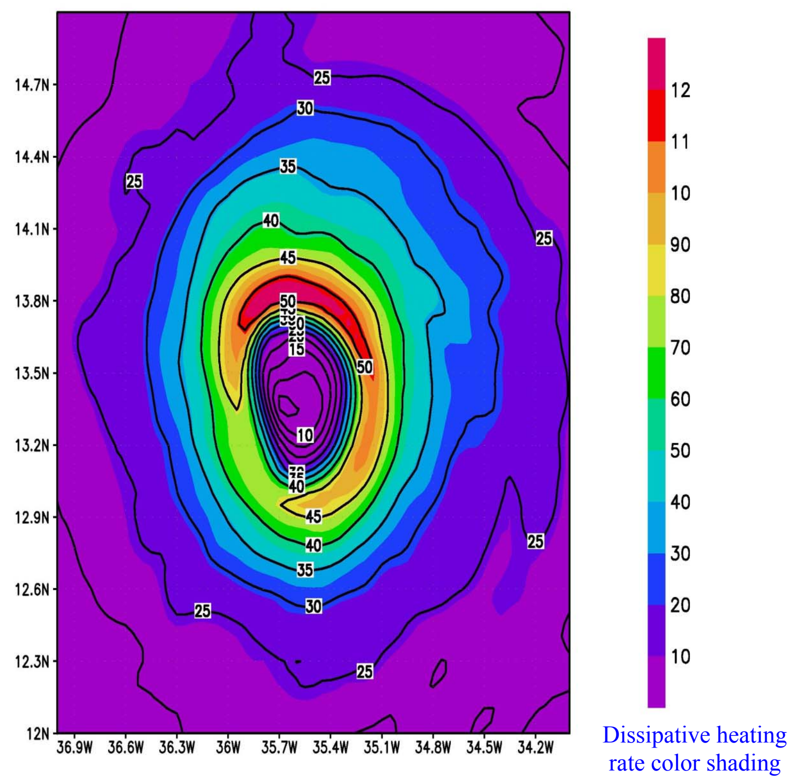


Figure 4. The dissipative heating implementation improves the COAMPS hurricane simulations. Left: maximum wind speed vs. time; Right: wind speed (contours) and dissipative heating rate (color shading). The simulation with the dissipative heating (red color on the left) strengthened the hurricane intensity by 15-25%

IMPACT/APPLICATION

The efforts on surface flux parameterization and understanding of the SST variability have important implications for the future development of COAMPS and mesoscale meteorological models in general. The parameterizations of surface flux and dissipative heating will significantly improve the air-sea interaction and enhance the hurricane forecast capability. The understanding of the SST variability will provide new insight on the coupled boundary-layer feedback mechanisms in the coastal air-sea interaction.

TRANSITIONS

The code for the dissipative heating and modified drag coefficient were transitioned to 6.4 COAMPS for further testing and evaluation.

RELATED PROJECTS

Related projects are NRL projects titled: 6.2 High-Resolution Test Bed for the Urban and Complex Terrain Environment and 6.2 High Resolution Soil Moisture and Precipitation Assimilation. A related project at NPS is Award # N0001405WR20338 for COAMPS surface flux and boundary layer parameterization study evaluation using aircraft measurements.

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